Hindawi
Journal of Nanomaterials
Volume 2023, Article ID 1004597, 15 pages
https://doi.org/10.1155/2023/1004597

Review Article

Compressive and Flexural Strength of Concrete with Different Nanomaterials: A Critical Review

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Received 12 July 2022; Revised 6 October 2022; Accepted 25 October 2022; Published 7 January 2023

Academic Editor: Albert Nasibulin

With recent technological advances, adding nanomaterials as a reinforcement material in concrete has gained immense attention. This review paper aims to report advances in the form of a one-stop shop catering to methods that focus on improving the quality of traditional concrete. Nanoparticles—the elementary form of nanomaterials—are proven to enhance the strength and longevity of concrete. Nanosilica, nanoalumina, nanometakaolin, carbon nanotubes, and nanotitanium oxide are modern nanomaterials that have demonstrated strong evidence of enhancing concrete quality, which supports infrastructure building and long-term monitoring. Nanoconcrete—an exciting prospect extending the boundaries of traditional civil engineering—exhibited increased compressive and flexural strength using elementary compounds. In particular, the rigorous research survey of many articles reveals an increase in compressive strength from 20% to 63% by replacing the cement with different nanomaterials in different percentages and flexural strength from 16% to 47%.

1. Introduction

The most common traditional material required for infrastructure construction is the mixture of cement, fine aggregate, coarse aggregate, and water—popularly known as concrete. Concrete is a porous substance that has to have its durability, usability, mechanical characteristics, and microstructural factors investigated [1]. Recent technological advances have resulted in the enhancement of several concrete properties exhibiting improvement over traditional concrete. Notably, the reduction of the water–cement (w/c) ratio [2] has subsequently resulted in contributing to the increased strength of the cement [3]. Additionally, the mix percentage has demonstrated an optimal condition by combining compendious nanoauxiliary concise [4–6]. Nanoconcrete employs constituent nanomaterials [7–13] that significantly improve the packing model structure in bulk characteristics. In addition to augmenting the properties of concrete, nanoparticles act as an excellent filler material. This review paper aims to report all the advances in nanomaterials-enhanced concrete that exhibit compressive and flexural characteristics [14].

The construction industry has immensely benefitted from nanomaterials throughout the review. In particular, the nanomaterials in cement and concrete products such as nano-TiO_2, nanoalumina, nanometakaolin, nano-SiO_2, nanoclay [15–17], and carbon nanotubes (CNTs) have improved the overall characteristics [18]. Inherently integrated with it are the filling features that contribute to increasing durability [19]. In addition, nanomaterials have been demonstrated to enhance microstructural features that are not explored in conventional construction engineering but are a mainstream genre of research for contemporary investigations. A thorough review of prior research sheds some light on this area, but a detailed analysis is needed. Still, an arching framework that incorporates characteristics of concrete containing NMK, TiO_2, and nanocellulose is lacking—which greatly motivates this research work. This review aims to advance the use of nanomaterials in contributing to the flexural and compressive strength of concrete.

2. Production of Nanomaterials

Even though the concept of creating nanomaterials through nanotechnology emerged in the late 1960s [20, 21], the aspect of strengthening the properties of concrete is relatively nascent—gaining momentum in recent decades. While all materials eventually convert into nanoparticles, Bharadwaz et al. [22] pointed out that these particles—solely attributed to their nanosize—have a stronger foothold compared with microbased components as far as filler materials are concerned. A top-down strategy [23] is inherently optimized that provides selection based on nanobehavioral expertise, appropriateness, and cost [24, 25]. Defined as the process of reducing larger structures to the nanoscale—while retaining their original features or chemical composition even at the atomic level—the top-down approach provides robustness and applicability over a wide variety of domain expertise [26]. In other words, mechanical attrition and etching processes break down bulk materials into nanoparticles [27]. The milling process is one of the strategies under the framework of top-down approaches [28, 29]. A milling machine's fundamental feasibility and accessibility corroborate changes without the need for chemicals or electronic devices. Another name for the top-down strategy is the present way of nanofabrication. However, the final product homogeneity and quality are inconsistent in the top-down approach.

High-energy ball millings can synthesize nanomaterials, nanograins, nanocomposites, and nano-quasicrystalline materials. In particular, by modifying the number of balls employed and their types, with an increase in the machine speed and the type of container used, the nanoparticles can alleviate the traditional shortcomings of the top-down approach [2, 30, 31]. During milling, plastic deformation, cold welding, and fracture are the factors influencing the deformation and transforming process of materials into the required shape. Milling not only breaks materials into smaller parts but also blends several particles or materials and transforms them into new phases of material composition in the case of the reactive ball milling technique, but this is not possible through dry and wet ball milling techniques. Although the milling process automatically reduces the size of materials, the mixture of various particles converts into a new material phase in the case of the reactive ball milling technique. The end product from a milling operation churns out materials in the new regime with lake-shaped strata in the case of the dry ball milling technique. However, refining can be carried out to obtain a more delicate structure based on the type and the size of the ball used corresponding to the milling technique. From a historical perspective, John Benjamin (1970) first administered the method of milling through the strengthening of alloy components for high-temperature structures [32]; this led to the first use of milling as an effective technique to produce oxide particles.

Contrary to the top-down approach, the bottom-up technique is employed when materials are assembled or self-assembled from atoms or molecular components. This methodology is helpful for most nanomaterials, such as nanosilica, nanoalumina, and nanoclay, which are widely used to improve the characteristics of concrete. This process is aptly termed molecular manufacturing or nanotechnology due to its indirect benefits, including synthesis and chemical formulation [24]. The critical difference between the various schools of thought is that the bottom-up method will produce a uniform and perfect structure of the nanoparticles compared to the top-down approach. This is explained by the fact that nanocrystals can automatically develop when atoms or molecules are well-organized or in crystalline form. A few strategies for this process include increased electronic conductivity, optical absorption, and chemical reactivity [25, 33].

Additionally, a significant reduction in the size of the particles—with the development of tidy surface atoms—combined with the enormous change in the surface energy leads to improved morphologies. Nanoparticles have become ideal candidates for advanced applications in electronic components and biotechnology. In the longer run, nanomaterials derive their applications toward boosting catalytic activity, wave sensing capabilities, novel pigments, and self-healing and cleaning properties in paint. The flip side of the coin, called flippin, exposes the severe drawbacks of the bottom-up strategy, including its high operational costs, the need for specialized knowledge in chemical applications, and its strict applicability to laboratory applications only [22, 34, 35].

3. Compressive Strength of Nanoconcrete Made with Nanomaterial

Numerous nanomaterials have been included in concrete since the development of nanotechnology in the building industry. Nanomaterials can be used to improve the durability and performance of concrete. The discussion of nanomaterials, such as nanometakaolin, nanosilica, nanoalumina, nanotitanium dioxide, CNTs, and nanocellulose, as well as their utilization in all types of concrete, will be further developed in this subsection in terms of their mechanical properties.

3.1. Nanometakaolin. NMK considerably enhanced the compressive strengths of cementitious materials, according to several studies [36–38]. Table 1 shows the 28-day compressive strength of cementitious materials treated with NMK. According to an extensive literature survey, adding the right amount of NMK to cementitious materials boosted their compressive strength [52, 53]. When the amount of NMK in a cementitious material exceeds the optimum level, the concrete compressive strength will reduce.

Meanwhile, too much NMK causes a weak interfacial transition zone (ITZ) and fewer contact points, which act as binding sites between cement particles [48, 54]. The addition of NMK to concrete increases its compressive strength.

Even though mixed proportion characteristics like w/c ratio and NMK content and curing conditions are the same, the optimum NMK contents are not the same based on a literature survey.

As a result, more research should be conducted and studied [22] to better understand the various effects of NMK on

Table 1: Twenty-eight-day compressive strength of concrete made with nanometakaolin.

Cementitious materials	w/b ratio	Replacement of NMK (%)	Compressive strength increment (%)	Maximum replacement of NMK (%)	References
Cement paste	0.27	4–15	8 ⟶ 20 ⟶ −15	10	[39]
	0.3	2–16	16 ⟶ 54 ⟶ −10		[30]
	0.33–0.49	2–14	8.6 ⟶ 59.4 ⟶ 46.6		[38]
	0.44	3–10	16 ⟶ 24.6 ⟶ 22	6	[23]
	0.5–0.59	2–10	10 ⟶ 63 ⟶ 20		[40]
Cement mortar	0.3	2–10	9.3 ⟶ 22.6 ⟶ −1.3	4	[41]
	0.4	5–10	28 ⟶ 20		[42]
	0.485	3	54		[43]
	0.5	2.5–10	15 ⟶ 34 ⟶ 19	7.50	[44]
	0.54	2–14	8.8 ⟶ 42 ⟶ 20	10	[45]
	0.6	5–15	23 ⟶ 8	5	[46]
Ordinary concrete	0.5	10	26.32		[47]
	0.53	3–10	42.2 – 63.1	10	[48]
UHPC	0.2	1–9	12 ⟶ −16.5	1	[49]
	0.2	1–10	8.5 ⟶ −8.5	1	[18]
SCHPC	0.35	1.25–3.75	12 ⟶ 17		[50]
SCC		1–5	12.7 ⟶ 42.2		[51]

The minus (−) sign implies decreasing the given attribute calculated concerning the reference one.

the compressive strength of concrete or mortar. In addition, some results are incongruent. The compressive strength of air-cooled slag (ACS)-blended cement mortar gradually lowered when the NMK content increased [48]. At 28 days, the compressive strength of mortar containing 8% NMK was marginally lower than that of the control mortar. According to Norhasri et al. [23], adding NMK to ultra-high-performance concrete (UHPC) with a compressive strength of 150 MPa at 28 days did not improve the early compressive strength. Although UHPC with 1% NMK had the maximum compressive strength, it was somewhat lower than the control UHPC. The early stability of UHPC was not compromised by the addition of NMK [55–57]. Furthermore, as the amount of NMK in UHPC increased, the material strength of compression dropped [58]. The compressive strength improved by up to 63% when the nanometakaolin content increased to 10%, and as the nanometakaolin content increased further, the mechanical characteristics deteriorated [59].

Almost all ages of hydration resulted in higher compression strength values than those reported for the typical ordinary Portland cement (OPC) paste. This increase in strength is primarily due to the pozzolanic reaction of free calcium hydroxide (CH), liberated from Portland cement hydration, with nanometakaolin to form excessive amounts of additional hydration products, primarily as calcium silicate hydrate (CSH) gel and crystalline CSH hydrates; these hydrates act as microfills, which reduce total porosity leading to an increase in the entire contents of binding centers in the specimens; consequently, an increase in the strength [60]. Thermal gravimetric analysis and scanning electron microscopy (SEM) were also used to monitor the hydration process (TG). These examinations indicate that NMK behaves as a filler to improve the microstructure and as an activator to promote the pozzolanic reaction [38].

3.2. Nanosilica. After 28 days, the compressive strength of concrete containing 3% NS improved by 20% compared to baseline concrete strength [43]. At 90 and 365 days, compressive strength testing revealed a similar pattern. Table 2 shows the existing compressive strength of cementitious materials with NS at 28 days.

The colloidal 40–50 nm NS effectively increased the compressive strength of 3% NS high-performance concrete to 33.25% for 24 hr. This improvement in strength corresponds to the 40 MPa compression strength. Also, the flexural strength exceeded 13.5% after 7 days [40]. The concrete with 3% NS as a replacement with cement substitute exhibited more compressive strength and a longer lifespan. The compressive strength of 3% NS was enhanced by 31.42% compared to the reference concrete [41]. The kind of NS is colloidal at 15 nm, and the surface area, particularly of NS particles, directly impacts the concrete compressive strength. The NS particles with a surface area of 51.4 m^2/g are the least beneficial in improving compressive strength. The w/b ratio influences the strength of NS concrete as well. The ideal amount of NS replacement is linked to the reactivity and accumulation level of the NS particles [42]. Ordinary concrete (sulfuric-acid-rain condition) with 0.3 w/b ratios substituted cement material with 2%–6%, which increased compressive strength by 15% [44]. Ordinary concrete with a 0.36 w/b ratio with 1% to 2.5% replacement of cement material shows increase in compressive strength up to 20.25% for 2% replacement and a 5% reduction in compressive strength for 2.5% replacement, corroborates the optimum replacement of NS is 2% [61]. The compressive strength of regular concrete increases from 1.75% to 7.2% with a w/c ratio of 0.3, 0.4, and 0.45, and NS content of 0.5%, 0.75%, and 1% as a replacement for cement [47]. Table 3 shows the tabulated results, which suggest that a 2% NS substitution is

Table 2: Twenty-eight-day compressive strength of concrete made with nanosilica.

Materials	w/c ratio	Replacement of NS (%)	Compressive strength increment (%)	Maximum replacement of NS (%)	References
Ordinary concrete (sulfuric-acid-rain condition)	0.3	2–6	10.5 ⟶ 15		[44]
	0.36	1–2.5	9.2 ⟶ 20.25 ⟶ −5	2	[61]
Ordinary concrete	0.3	0.5–1	1.75 ⟶ 2.5		[47]
	0.35	0.5–1	1.05 ⟶ 1.84		[47]
	0.4	0.5–1	3.3 ⟶ 7.2		[47]
	0.45	0.5–1	5.59 ⟶ 10.39		[47]
	0.4	0.75–3	20		[43]
	0.4	3	31		[41]
HPC	0.4	3	33		[40]

The minus (−) sign implies decreasing the given attribute calculated concerning the reference one.

Table 3: Twenty-eight-day compressive strength of concrete made with nanotitanium dioxide.

Materials	w/c ratio	Replacement of NT (%)	Compressive strength increment (%)	Maximum replacement of NT (%)	References
Mortar	0.5	0.25 ⟶ 0.75 ⟶ 1.25 ⟶ 1.75	10.5 ⟶ 19.33 ⟶ 15.07 ⟶ 4.27	0.75	[62]
Mortar with 10% of black rice husk ash	0.35	0.5 ⟶ 1 ⟶ 1.5	1.48 ⟶ 4.75 ⟶ 13.22	1.5	[63]
RPC		1, 3, 5	18.55	3	[64]
HPC	0.25	1.50	23		[65]
SCC with ground granulated blast-furnace slag (GGBS)	0.4	1 ⟶ 2 ⟶ 3 ⟶ 4	2.7 ⟶ 26.5 ⟶ 36.4 ⟶ 27.8	3	[66]
RPC		1 ⟶ 3 ⟶ 5	43.43 ⟶ 74.9 ⟶ 87	5	[67]
Concrete	0.48	2	23	2	[68]
SCGPC		2 ⟶ 4 ⟶ 6	−3.43 ⟶ 7.7 ⟶ 3.4	4	[69]

The minus (−) sign implies decreasing the given attribute calculated concerning the reference one.

optimal and any further increment in NS content diminishes strength [70].

According to the study, up to 3% of NS doses can improve mechanical characteristics, potentially due to pozzolanic activity, pore structure refinement, and filling effect. Compressive strength increases as the NS content grows, reaching 33% for an NS proportion of 3%.

The compressive strength was seen to increase to 2% nanosilica substitution before significantly declining. Due to the increased hydration by nanosilica, there is a more significant consumption of $Ca(OH)_2$ in the early stages (1–7 days of curing). This outcome favors a 2% substitution of nanosilica in cement by weight. The pozzolanic reaction of nanosilica and CH produces well-compacted hydration products that coat the unhydrated cement and slow the rate of hydration. Additionally, hydration products plug the pores in the cement, reducing the amount of water that can reach the anhydrate cement particles and reducing the strength above 2% nanosilica replacement [71].

3.3. Nanotitanium Dioxide. Most researchers agreed that using NT particles might improve the compressive strength of concrete to some extent. The effect of NT on the compressive strength of concrete is shown in Table 3.

TiO_2 nanoparticles with an average diameter of 15 nm were used in four different amounts of 0.25%, 0.75%, 1.25%, and 1.75% by weight of cement with a w/c ratio of 0.5 [72]. The 0.75% NT increases the mortar's compressive strength by 19.33% after 28 days. The strength decreased as the NT content increased; hence, the optimum NT content is 0.75% [62]. In 10%, 20%, and 30% of the fractions, untreated black rice husk ash (BRHA) was used to replace cement. When nano-TiO_2 doses of 0.5%, 1.0%, and 1.5% were added to blended cement, the compressive strength increased to 13.22% [63]. The compressive strength of concrete containing 20% fly ash (FA) can be enhanced by 18% by using 3% NT, according to Li et al. [64]. It was discovered that NT at a dose of 3 wt% improved the compressive strength of self-compacting concrete (SCC) with GGBS and a w/c ratio of 0.4 the most. The flexural strength of nano SiO_2 coated TiO_2 reinforced reactive powder concrete (NSCTRRPC) reached a maximum of 9.77 MPa when the range of NSCT was 3% and increased 83.3%/4.44 MPa compared with reactive powder concrete (RPC) without NSCT. Even while the strength of flexural NSCTRRPC was slightly lesser than that of plain RPC when the NSCT content was 5%, it was still much more than bare reactive powder concrete. It could be related to a decrease in hydration speed caused by water absorption. At 28 days, the ideal level of NS content was 5.0%. The use of nanoparticles as cementitious materials increased the compressive strength of concrete, as shown in Table 3. After 28 days of curing, the compressive strength of concrete can enhance up to 22.71% by replacing 2%

Table 4: Twenty-eight-day compressive strength of concrete made with nanoalumina.

Materials	w/c ratio	Replacement of NA (%)	Compressive strength increment (%)	Maximum replacement of NA (%)	References
Mortar	0.79	1, 3, 5	20 ⟶ 15 ⟶ 36.00	5.00	[75]
Mortar	0.35	1, 2, 3	16.00 ⟶ 12 ⟶ 12	1	[76]
Concrete	0.44	1, 2, 3	13.00 ⟶ 4 ⟶ −1		[77]
Concrete	0.33	0.5, 0.75, 1	6 ⟶ 28 ⟶ 46	1	[78]
Mortar with 10% of black rice husk ash	0.49	1, 2, 3	1 ⟶ 11 ⟶ 16	3	[79]
Concrete	0.48	3, 5, 7	16.67 ⟶ 30.13 ⟶ 23.58	5	[80]
Concrete		2, 3	3.32 ⟶ 5.3	3	[81]
Mortar	0.5	0.5, 1, 1.5	7 ⟶ 10.6 ⟶ 11.4	1.50	[82]

The minus (−) sign implies decreasing the given attribute calculated concerning the reference one.

cement with nanotitanium oxide particles (relative to plain concrete). Titanium oxide was introduced to specimens with wollastonite; the compressive strength increased initially, and then declined. The best combination was 4% NT without wollastonite [69, 73].

According to the study, the optimal dose of NT is 3%, which boosts compressive strength by up to 23%; however, increasing the NT concentration diminishes mechanical characteristics.

The review paper's findings revealed the diffraction intensity of several CH and C3S crystals specimens. First, with increasing hydration age, C3S diffraction apex intensity declined, while CH diffraction apex intensity increased in the base specimen. But even after 28 days, C3S had not fully hydrated. Second, utterly different change tendencies were visible in the strength of the two CH diffraction peaks, as evidenced by the variance in X-ray diffraction (XRD) results between the base specimen and the additional specimen. When nano-TiO_2 was used to replace cement, the intensity of the CH (101) crystal plane grew early on, whereas the power of the (001) crystal plane significantly dropped. When the cement was replaced with nano-TiO_2, the amount of CH crystal did not increase after 1 day. Therefore, the rise in hydrated products should not be cause of the improvement in early strength. Third, the intensity of CH at evening ages increased so slowly after the slag powder was applied to the cement mortar that it reduced after 14 days, and the power of CH was significantly lower than that of other specimens without the slag powder. This meant that CH was used to hydrate the slag powder, which helped to increase strength in the evening hours [74].

3.4. Nanoalumina. Most researchers agreed that using nano alumina (NA) particles might improve the cementitious composites and compressive strength. Table 4 shows the effect of NA on the compression strength of cementitious material.

After 7 days of the curing period, the addition of NA increased by 1%, 3%, and 5% replacement by 46%, 27%, and 19.3%, respectively. It was discovered that the 1% replacement level of NA provides the best early strength. After 28 days of the curing period, the compressive strength of the 0% replacement level was found to be 13.69 MPa; the addition of NA resulted in increase of 20%, 15%, and 36%, respectively, whereas 5% replacement resulted in better compressive strength after 28 days [75]. The 1% nanoalumina content to instars increased their compressive strength by up to 16% at room temperature. Higher concentrations of NA (>2%) reduced the power mortars to their original level. One percent nanoalumina was added at temperatures up to 800°C; the residual compressive strength remained more elevated than the actual amount [76]. When OPC is substituted with NA, the compressive strength increases by 1%. The 28-day compressive strength increased by 13% when a 1% NA replacement level was utilized instead of a 0% NA combination. The compressive strength of concrete cubes was boosted by introducing NA into the matrix; the compressive strength of composites rose by 33.14% at 28 days when the proportion of NA was 1% of the cement by weight [78].

The addition of rice husk ash boosted the 28-day compressive strength of samples, with 10% replacement of rice husk and 3% NA giving the greatest compressive strength of 16.6%. The compression strength decreases as the rice husk content increases [79] by replacing 1% of cement with nanoalumina particles; concrete 28-day compressive strength was increased by 4.03%; when the concentration of NA was increased from 1% to 3%, the compressive strength improved from 4.03% to 8.00%. As a result, cement hydration was hastened, resulting in higher amounts of reaction products. Also, nanofiller nano-Al_2O_3 particles regain the concrete particle packing density and improve the microstructure. As a result, the volume of larger pores in the cement paste is reduced [80]. The compressive strength of all the tested mortars decreases as the amount of Al_2O_3 nanopowder in their composition increases. When 0.5% Al_2O_3 nanopowder was added, the decline was 7%, 10.6% with 1% and 11.4% with 1.5% compared with the reference mortar. According to several studies, adding Al_2O_3 nanopowder to mortars can increase their compressive strength [82].

According to the study, the optimum concentration of nanoalumina was 5%, at which point compressive strength increased by 36%.

The rapid consumption of $Ca(OH)_2$ produced during Portland cement hydration, which is connected to the high reactivity of nano-Al_2O_3 particles, is likely what caused the increase in the compressive strength of concrete containing nanoalumina. As a result, the cement's hydration was sped up, and more reaction products were generated. Additionally, nano-Al_2O_3 particles restore the concrete's particle

Table 5: Twenty-eight-day compressive strength of concrete with carbon nanotubes.

Materials	w/b ratio	Replacement of MWCNT (%)	Compressive strength increment (%)	Maximum replacement of CNT (%)	References
M30 grade of concrete	0.4	0.015, 0.03, and 0.045	2.75 ⟶ 26.7		[83]
Concrete		0.25 and 0.5	7.14 ⟶ 15.7		[84]
Mortar	0.55	0.05, 0.1, and 0.2	15 ⟶ 8 ⟶ 10	0.05	[85]
Concrete	0.4	0.1, 0.2, 0.3, 0.4, and 0.5	7.11 ⟶ 18.2 ⟶ 22.56 ⟶ 24.5 ⟶ 27.35		[86]
SCC	0.45	0.1, 0.3, and 0.5	16.6 ⟶ 24 ⟶ 38.62		[87]
Ultra high strength concrete (UHSC)	0.2	0.05, 0.1, and 0.15	4.6 ⟶ 2.1 ⟶ −1.97	0.1	[88]
Concrete	_	0.0.2, 0.03, 0.05, and 0.09	83.33 ⟶ 97.22 ⟶ 80.55 ⟶ 63.88	0.03	[89]

The minus (−) sign implies decreasing the given attribute calculated concerning the reference one.

packing density and enhance its microstructure as a nanofiller, decreasing the volume of bigger pores in the cement paste. The outcomes align with those reported by other researchers [80]—dosage of the samples NA1, NA2, NA3, and control at various temperatures. The compressive strength decreased when the dosage of nanoalumina rose to 2% and 3%, although it remained higher than the control samples. The ITZ may have become loose due to the excessive aggregation of nanoalumina particles, which may have surrounded fine aggregates [76].

3.5. Carbon Nanotubes. According to most studies, the compression strength of cementitious material could be increased to some extent with CNT particles. Table 5 shows CNT's effect on cementitious material's compressive strength.

The compressive strength of concrete increased by up to 26.7% when functionalized multiwalled carbon nanotube (MWCNT) was used in place of 0.045% cement. MWCNT in cement shows an improvement in the stiffness of the CSH gel, making the composite more substantial. An explanation for the improved mechanical properties of concrete could be that the MWCNTs occupy the nanostructure in MWCNT concrete, making them more crack resistant throughout the loading period [83]. Modified MWCNTs were disseminated in cement mortars to improve their mechanical qualities. When pure MWCNTs were used, the compressive strength of cement mortars was significantly increased—incorporating 0.50 wt%. Percent MWCNTs resulted in a 15.7% increase in compressive strength, whereas containing 0.250 wt%. Percent MWCNTs resulted in a 7.14% increase in compressive strength [84]. The cement mortar's compressive strength was improved by adding CNTs. The maximum enhancement obtained when utilizing 0.05% CNTs is up to 15%; however, the stability decreases as the CNT content increases [85]. According to the strength of compression data, the percentage increase in compressive strength for 0.1% and 0.5% is 7.11% and 27.35%, respectively, for 28 days. The dispersion of CNTs is primarily responsible for the increase in results. The increase in the number of highly stiffened CSH in the presence of CNTs is the second explanation for the increase in features [86]. The compressive strength of SCC with 0.%, 0.3%, and 0.5% MWCNT concentration increased to 38.62% [87]. The most significant gains in the mechanical characteristics of cement-based materials were found to be at low concentrations of MWCNTs (0.05%). The compressive strength rose to 4.6% for a 0.05% MWCNT in the current investigation; however, as the content of MWCNT increases, the power drops; hence, the optimum content is 0.05% [88].

It was determined from various sources that the maximum concentration of CNT was 0.1%. The compressive strength of UHSC rises by up to 2.1%.

At 80°C, the CNTs were functionalized in a solution of concentrated H_2SO_4 and HNO_3. The removal of carboxylate carbonaceous fragments that could adversely influence the mechanical strength of the concrete due to their interaction with cement hydration products was discovered to require the functionalization of acetone washing [89].

The ability to synthesize novel hybrid nanostructured materials in which CNTs and carbon nanofibers (CNFs) connected to cement particles and enabled good dispersion of the carbon nanomaterials in the cement was made possible by employing cement particles as catalysts and support material. Two chemical vapour deposition reactors were used to create this hybrid material, which is easily included in the production of commercial cement [90, 91]. The fluidized bed reactor's product yield was significantly enhanced. The research using TEM, SEM, XRD, thermogravimetric analysis, and Raman measurements revealed the process for producing CNTs and CNFs at low temperatures and high yields to be highly effective. After 28 days of curing in water, tests on the physical characteristics of the cement hybrid material paste revealed up to a twofold increase in compressive strength and a 40-fold increase in electrical conductivity [90, 91].

The increased compressive strength may be related to the fact that the addition of CNTs caused the microcracks to start and spread more slowly because they were evenly distributed throughout the cement mortar. The mechanical strengths of the mortar may be improved by adding CNTs to improve the adhesion between the hydration products. Additionally, it is possible that the presence of CNTs led to the production of additional CSH and the consumption of CH [85, 86].

3.6. Nanocellulose (NC). According to most studies, the compression strength of cementitious material could be increased to some extent with nanocellulose particles. Table 6 shows NC's effect on cementitious material's compressive strength.

Table 6: Twenty-eight-day compressive strength of concrete made with nanocellulose [92–94].

Materials	w/c ratio	Replacement of NC (%)	Compressive strength increment (%)	Maximum replacement of NC (%)	References
Concrete	0.3	0.05, 0.1, 0.2, and 0.3	25 ⟶ 17 ⟶ 11 ⟶ 3	0.05	[92]
Concrete	0.15	0.005, 0.01, and 0.015	8 ⟶ 3 ⟶ 1	0.005	[93]
Concrete	0.35	0.2 and 0.1	10 ⟶ 17		[94]

Table 7: Twenty-eight day flexural strength of concrete made with nanometakaolin.

Materials	w/b ratio	Replacement of NMK (%)	Flexural strength increment (%)	Maximum replacement of NMK (%)	References
Cement paste	0.3	2–14	14 ⟶ 36 ⟶ −25	10	[33, 52]
	0.33–0.49	2–14	3.9 ⟶ 58 ⟶ 38		[38]
	0.5	2.5–10	6.4 ⟶ 29 ⟶ 19	7.50	[44]
	0.6	5–15	8–4	5	[46]
Ordinary concrete	0.5	0.1	0.2587		[47]
	0.53	3–10	0–46.8	10	[48]
RPC	0.175	2–5	3.16–7.35	5	[71]
FRCC	0.3	2–14	16 ⟶ 67 ⟶ 54	10	[55]
SCC		1–5	14.5 ⟶ 33.8		[51]
SCHPC	0.35	1.25–3.75	10 ⟶ 27.5		[50]

The minus (−) sign implies decreasing the given attribute calculated concerning the reference one.

The compressive strength of concrete with a cellulose content of 0.05% and 0.10% increased by 26% and 17%, respectively. In contrast, combinations with 0.20% and 0.30% NC had less apparent impacts, rising by 11% and 3%. The effect of NC on hydration kinetics and hydrate characteristics may be linked to the higher compression strength in the presence of nanocellulose [92]. The results demonstrate that NC mortar samples improve compressive strength after 7 days of curing; the UHP mortar sample, which included 0.005 wt% NC, had the most excellent compressive strength value of 184 MPa of binders. In this situation, the compressive strength was roughly 8% higher than the control mortar and 4%–8% higher than the 0.01% and 0.015% NC mortars. Because of its high specific surface, NC probably provides close spacing and strong adhesion to the cement matrix, boosting density and impacting compressive strength development [93]. Adding 0.2% and 1% NC raises the strength of the material by 10% and 17%, respectively. The hydrophilic properties of CNCs, which result in increased hydration products, may be responsible for increasing compressive strength. Furthermore, using 0.2% and 1% CNC decreases cement volume while maintaining compressive strength [94].

With an optimum dose of NC of 0.1%, the compressive strength increases by up to 17%, while a higher amount of NC lowers the mechanical characteristics.

The greater compressive strength in the presence of cellulose filaments (CF) may be related to the effect of nanocellulose on the hydration kinetics and the properties of hydrates. According to research [92], the hydrophilic and hygroscopic nanocellulose may add more water to the cementitious matrix to raise the degree of hydration and improve mechanical performance.

4. Flexural Strength of Nanoconcrete Made with Nanomaterial

4.1. Nanometakaolin. As shown in Table 7, NMK has the potential to improve cementitious material flexural strength significantly. The optimum concentration of NMK is primarily between 8% and 10% [49, 95]. The results showed that fiber-reinforced cementitious composite (FRCC) with 10% NMK exhibited a 67% increase in flexural strength after 28 days compared with control FRCC. However, flexural strength rapidly decreased when the NMK concentration was increased. The effect of NMK addition on SCC as a partial replacement by weight of cement at four percentages (0%, 1%, 3%, and 5%) increased flexural strength by up to 33.8% [51].

According to the findings, the optimal dose of NMK is 10%, which enhances flexural strength by 46.8%; however, increasing the concentration of NMK diminishes mechanical characteristics.

Results illustrate the relationship between flexural strength variation and curing age for blended cement mortars containing NMK. As the curing age and NMK addition rise, flexural strength also increases. At 60 days of hydration, the flexural strength increases as the NMK addition increases up to 7.5% and then decreases after a 10% addition. The pozzolanic reaction of FA and NMK with free lime released during OPC hydration and the physical filling of the NMK platelet particles inside the interstitial spaces of the FA-cement skeleton is what causes the increase in flexural strength. However, the NMK platelet particles act nanosize enhanced because of the interfacial zone. At 7.5% NMK addition, the increase in flexural strength was 2.3-fold. The reduction of flexural strength at a later age and 10% NMK addition may be due to the agglomeration of NMK particles around cement grains.

Table 8: Twenty-eight-day flexural strength of cementitious materials with NS.

Materials	w/c ratio	Replacement of NS (%)	Flexural strength increment (%)	Maximum replacement of NS (%)	References
Ordinary concrete (sulfuric-acid-rain condition)	0.36	1–2.5	5 ⟶ 16.8 ⟶ −0.26	2	[61]
UHPC	0.4	4–5	0 ⟶ 34.6 ⟶ −26.9	4	[96]
UHPC with 2.5% steel fibers	0.4	4 NS + 2.5 steel fibers	10.4–24		[96]
HPC	0.31	0.5, 1, 1.5, 2, 2.5, and 3	10.7 ⟶ 21.1 ⟶ 28.8 ⟶ 36.5 ⟶ 29 ⟶ −22	2	[71]

The minus (−) imply decreasing the given attribute calculated concerning the reference one.

Table 9: Twenty-eight-day flexural strength of cementitious materials with NT.

Materials	w/c ratio	Replacement of NS (%)	Flexural/split tensile strength increment (%)	Maximum replacement of NT (%)	References
Mortar	0.5	0.25 ⟶ 0.75 ⟶ 1.25 ⟶ 1.75	9 ⟶ 15.1 ⟶ 13.2 ⟶ 7.5	0.75	[62]
Mortar	0.58	1–5	61	3	[98]
RPC		1, 3, 5	47.07	3	[64]
HPC	0.25	1.50	18		[65]
SCC with GGBS	0.4	1 ⟶ 2 ⟶ 3 ⟶ 4	5.5 ⟶ 14.8 ⟶ 27.7 ⟶ 16.6	3	[66]
RPC		1 ⟶ 3 ⟶ 5	5.97 ⟶ 12.26 ⟶ 10.32	5	[67]
SCGPC		2 ⟶ 4 ⟶ 6	6.8 ⟶ −8.18 ⟶ −2.58	2	[69]

The minus (−) sign denotes decreasing the estimated attribute concerning the reference one.

4.2. Nanosilica. Most researchers agreed that using nanosilica particles could somewhat improve the flexural strength of cementitious material. Table 8 summarizes NS's outcome on the cementitious material's flexural strength. According to Jalal et al. [46], high-performance SCC with 2% NS and 10% silica fume (SF) exhibited better flexural strength than the reference mix at 28 days, with an optimum increase of 59%; however, the increased flexural strength was demonstrated to slow down as the age of the concrete increased. They also discovered that NS-only concrete had considerably lower flexural strength than NS-plus-SF-admixed concrete. Ordinary concrete with a w/c ratio of 0.36 has a cement replacement rate of 1%–2.5%, with a maximum replacement rate of 2%. Because increasing the NS content diminishes strength, the study determined that a 2% replacement is the best option [61]. The flexural strength of UHPC with a w/c ratio of 0.4 and nanosilica replacement with cement 4%–5% increases to 34.6%, and at 5% replacement of NS, the flexural strength decreases to 26.9%; thus, in this review, it is concluded that the optimum content of NS is 4%, and when it is combined with 2.5% steel fiber and 4% NS, the strength increases to 34.6%. In the high-performance concrete with a w/c ratio of 0.31 and NS replacement varying from 0.5% to 3%, flexural strength increased from 10.7% for 0.5% NS to 36.5% for 2% NS with a 0.5% increment. It then decreased to 22% for 3% NS with further addition of NS at about 3%, indicating maximum content is 2% [71]. According to Li et al. [97], adding 1% NS increased flexural strength by 41% and 35% for UHPC under the combined curing conditions of 2 days heat and 26 days conventional curing, respectively, at 0.16 and 0.17 w/b ratios control UHPC matrix under the collective curing conditions of 2 days heat and 26 days conventional curing. On the other hand, adding more than 1% NS resulted in a slight increase in flexural strength. Table 8 depicts the effects of NS at different doses throughout 28 days. According to the study, up to 3% of NS doses can increase mechanical qualities, which might be related to pore structure refinement, pozzolanic effect, and filling effect. Flexural strength rises as the NS percentage rises, reaching 34.6% for an NS content of 4%.

NS's sizeable specific surface area and high pozzolanic activity boost the strength gained at young ages when it is added to mortars and concrete. More CSH gel and compact structures are produced due to the above-mentioned process. Beyond the 2% addition, the amount of nanosilica exceeds the amount of released lime, which lessens the pozzolanic activity. It may be established that 2% of nanosilica is the ideal amount in high performance steam-cured concrete.

4.3. Nanotitanium Dioxide. The effects of NT on the flexural strength of cementitious composites are shown in Table 9.

With a water-to-cement ratio of 0.5, with four different amounts of 0.25%, 0.75%, 1.25%, and 1.75% by weight cement, TiO_2 nanoparticles with an average diameter of 15 nm were used. The 0.75% NT content raised the mortar flexural strength by 15.1% after 28 days; however, increasing the NT content lowered the power; thus, the optimum value is 0.75% [62]. The effects of nano-TiO_2 (NT) with a percentage replacement of cement of 1%, 2%, 3%, 4%, and 5%. The results demonstrate that 3% NT increases tensile/flexural

Table 10: Twenty-eight-day flexural strength of cementitious materials with NA.

Materials	w/c ratio	Replacement of NA (%)	Flexural strength increment (%)	Maximum replacement of NA (%)	References
Mortar with 10% of black rice husk ash	0.49	1, 2, 3	−0.1 ⟶ 11.6 ⟶ 16.7	3	[79]
Concrete		2, 3	5.16 ⟶ 6.7	3	[81]
Mortar	0.5	0.5, 1, 1.5	10 ⟶ 12 ⟶ 13	1.5	[82]

The minus (−) sign implies decreasing the given attribute calculated concerning the reference.

strength by 61% (i.e., toughness) and that increasing the NT level reduces power; thus, the optimum content is 3% [98]. Because NT particles can improve the ITZ of cementitious material, Li et al. [64] found that adding NT to cementitious composites can significantly increase long-term and short-term strength. With 3% of NT, the flexural strength increases to 47% [64].

HPC increases flexural strength by 18% [65] with a 1.5% NT and a water-to-binder ratio of 0.25. The effect of different NT dosages on the flexural strength of cementitious composites was evaluated by Nazari and Riahi [66]. They discovered that adding 3 wt% NT at 28 days raised flexural strength by 27.7%. Presence of NSCT does not affect the compressive strength of the composites during the 3-day curing phase, but it does throughout the 28-day curing phase. The NSCTRRPC compressive strength peaked at 111.75 MPa after 28 days, increasing 12.26%/12.2 MPa above the ordinary RPC [99]. This is because NSCT generates more negative charges on the surface of NT, making it simpler to disperse in water via electrostatic repulsion [67]. When titanium oxide was introduced to specimens with wollastonite, the tensile strength increased and dropped. The flexural strength of samples containing titanium oxide but no wollastonite was superior to wollastonite models. The best combination was found to be 4% NT without wollastonite [69]. Based on the previous study, the improvement in bending strength of NT cementitious composites could be related to the following factors.

On one hand, cement hydration products would deposit on nanoparticles because of the particles' high surface activity, and as a result, the nanoparticles would become the nucleus of agglomerates. The nucleation effect is the name for this phenomenon. This method's NT dispersed in the matrix can improve the matrix compactness and microstructure [100, 101]. NT has a nanocore action that induces fracture deflection and limits crack extension [67]. According to the study, the optimum dosage of NT for RPC is 3% flexural strength up to 87%; increasing the NT content diminishes the mechanical characteristics.

In the opinion of the reviewers, the following elements may be to blame for the enhanced flexural/split tensile strength of NT-engineered cementitious composites. The nucleation effect is where cement hydration products initially deposit on nanoparticles due to their extensive surface activity and then multiply to generate conglomerations with the nanoparticles functioning as the "nucleus." According to this strategy, the matrix's microstructure and compactness can be improved by the NT disseminated throughout it [102]. On the other hand, the nanocore action of NT may result in fracture deflection and stop cracks from expanding to generate a toughening effect.

4.4. Nanoalumina. Most studies agreed that adding NA particles to cementitious composites could improve their flexural strength. Table 10 summarizes the possible changes of NA on the flexural strength of cementitious material.

The addition of rice husk boosted the 28-day flexural strength of samples, with 10% replacement of rice husk and 3% nanoalumina giving the greatest flexural strength of 17%. The flexural strength decreases as the rice husk content increases [79]. It was discovered that raising 2% and 3% of NA increased its power up to 3%, respectively, in nonfiber designs (equivalent to a 5% increase). When the treatment time was increased to 28 days and the nanoalumina concentration was raised by 2% and 3%, this value climbed to 5.5 (equivalent to a 5% increase) and 5.58 MPa (equal to a 7% increase) [81]. By 7 days of age, however, nanoalumina percent had climbed to 2% and 3%. This parameter had increased to 5.21 (corresponding to a 5% increase) and 5.33 MPa, respectively (equivalent to a 7% increase). The development of pozzolanic reactions and the microstructure density of the mortar matrix improves the transitional area and, as a result, improves the adhesion of the fibers and matrix, as well as increasing the strength of the elongation of the fiber during flexural loading [81], can explain this trend. The flexural strength was reduced by around 10% by adding 1% and 1.5% nanopowder, regardless of the nanopowder amount [82].

According to the findings, the optimum concentration of nanoalumina was 3%, with a 16.7% increase in flexural strength.

The development of pozzolanic reactions and the microstructure density of the mortar matrix, which enhances the transitional area and, in turn, improves the matrix's adhesion property, while also strengthening the elongation during flexural loading, can be interpreted as the cause of the increase in flexural strength by adding nanoalumina [81].

4.5. Carbon Nanotubes. Most researchers agreed that CNT particles might improve the bending strength of cementitious material to some extent. Table 11 shows the effect of CNT on the bending strength of cementitious material when CNT is added.

The bending strength of mortars was significantly improved simultaneously when pristine MWCNTs and all contents were used—incorporating 0.250 wt% percent MWCNTs resulted in a 3% increase in flexural strength, while 0.50 wt% percent MWCNTs resulted in a 10.4% increase in bending strength [84]. The cement mortar bending strength was improved by adding CNTs [103]. When added CNTs increase, the flexural

Table 11: Twenty-eight-day flexural strength of cementitious materials with CNT.

Materials	w/b ratio	Replacement of MWCNT (%)	Flexural strength increment (%)	Maximum replacement of MWCNT (%)	References
Concrete		0.25 and 0.5	$3 \longrightarrow 10.4$		[84]
Mortar	0.55	0.05, 0.1, and 0.2	1, 7, and 28		[85]
Concrete	0.4	0.1, 0.2, 0.3, 0.4, and 0.5	$10.25 \longrightarrow 15.4 \longrightarrow 19.23 \longrightarrow 20.5 \longrightarrow -1$	0.4	[86]
SCC	0.45	0.1, 0.3, and 0.5	$21.2 \longrightarrow 32.9 \longrightarrow 38.6$		[87]
UHSC	0.2	0.05, 0.1, and 0.15	$7.5 \longrightarrow 3.33\% \longrightarrow -0.66$	0.05	[88]

The minus (−) sign implies decreasing the given attribute calculated concerning the reference one.

Table 12: Flexural strength of cementitious materials with NC at 28 days.

Cementitious materials	w/b ratio	Replacement of NC (%)	Flexural strength increment (%)	Maximum replacement of NC (%)	References
Concrete	0.3	0.05, 0.1, 0.2, and 0.3	$16 \longrightarrow 19 \longrightarrow 21 \longrightarrow 20$	0.20	[92]
Concrete	0.15	0.005, 0.01, and 0.015	$37.3 \longrightarrow 18.53 \longrightarrow 1.9$	0.005	[93]
Concrete	0.35	0.25, 0.5, 0.75, 1, 1.75, 0.5, 1, and 1.5	20, 12.5, 10, 7.5, 6.25, and 5		[104]

strength improves up to 28% for the 0.2% of CNTs [85]. The percentage increase in compressive strength for 0.1% and 0.4% was 10.25% and 20.5%, correspondingly, for 28 days. A further increase in the content of 0.5% caused the flexural strength to decrease, indicating that the optimum range was 0.4%. The dispersion of CNTs is primarily responsible for the increase in results. The increase in the number of highly stiffened CSH in the presence of CNTs is the second explanation for the increase in features [86]. The compressive strength of SCC with 0.1%, 0.3%, and 0.5% MWCNT increased by 38.6% [87]. The flexural strength rose to 3.33% for a 0.1% MWCNT in the current study; when the content of MWCNT grows, the flexural strength falls; therefore, 0.1% is the ideal content [88].

According to various literary works, the ideal amount of CNT is 0.4%, and flexural strength improves up to 20.5%.

Improvement in flexural strength and tensile strength is due to bridging the crack surfaces in the presence of CNTs. It is also noted that with CNTs, concrete density decreases with the density value reducing from 310 to 290 kg/m^3. The reason is decreased pore wall discharge and uniform pore size. Also, the workability of the paste was increased as a superplasticizer was used. The basic properties of cement and the process of gaining strength in concrete include components of different shapes. CSH is a cloud-like structure, CH is like the rose of stone, and calcium sulfur aluminate hydrates are needle structures that produce pores due to the different shapes of frames. Homogeneous dispersion of CNTs made concrete denser as dispersed CNTs filled voids, increasing its crack resistivity [86].

4.6. Nanocellulose. Table 12 shows the outcome of NC on the flexural strength of cementitious material.

The flexural capacity of the reference concrete was 4.84 MPa, while the flexural capacities of NC concentrations of 0.05%, 0.10%, 0.20%, and 0.30% as a replacement for cement were 5.62, 5.75, 5.84, and 5.81 MPa, respectively. This translates to increased flexural strength of 16%, 19%, 21%, and 20%, respectively. This reveals that increasing the content of CF increases flexural strength by up to 21% for a 0.2% NC content. Expanding the scope of NC diminishes flexural strength; thus, the ideal range is 0.2% [92]. The results showed that the sample with 0.005% of NC has higher flexural strength, around 37.3%, than the control mix; however, further increases in % of NC, the flexural capacity decreases; hence, the optimum range of NC is 0.005% [93]. Adding nanocellulose increases the mechanical qualities of the material. Adding NC as a 0.2% replacement for cement increases flexural strength by 20% [105]; expanding the scope of NC further reduces flexural strength but still leaves it higher than the reference mix; thus, the optimum range is 0.2% [104].

According to numerous studies, the ideal content of NC is 0.2%, and flexural strength rises by up to 20%. The above results reveal that the effect of CF on flexural capacity is twofold: (1) an increased first peak strength (rupture strength) associated with the nanometric properties of CF. This alters the properties of the cement paste matrix at the microstructure level (as further discussed afterward); (2) an enhanced toughness associated with the high aspect ratio and the tensile strength of CF, which contribute toward maintaining the peak load for a prolonged range of microdeflections prior to failure, thereby increasing the cracking resistance. The observed effect of CF on composite fracture behavior is driven by the contribution of the filaments as a nanoreinforcement. Possible mechanisms involved in the CF effect on composite fracture behavior may include: (1) filament bridging capacity driven by their high aspect ratio and fibrillated morphology, (2) filament resistance to rupturing owing to their tensile properties, and (3) the filament-matrix interfacial bond stemming for the potential interaction between the omnipresent –OH groups on CF surface and cement hydrates by hydrogen bonding. In this mechanism, irrespective of the effect of CF on

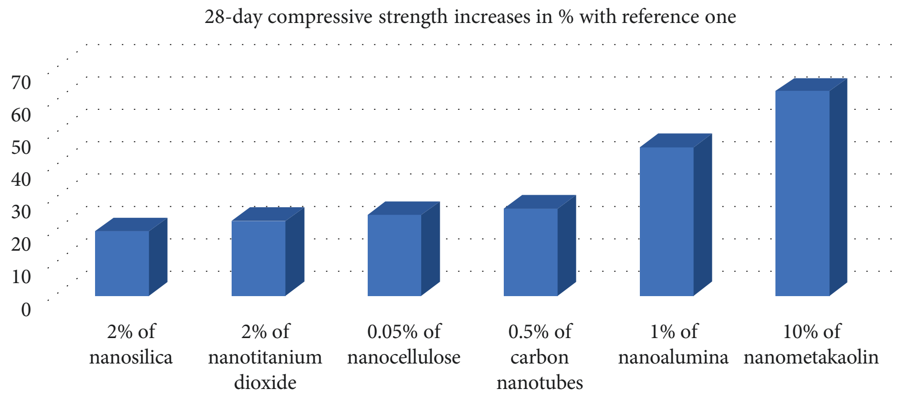

Figure 1: Twenty-eight-day compressive strength increase (%) [48, 61, 65, 78, 83, 92].

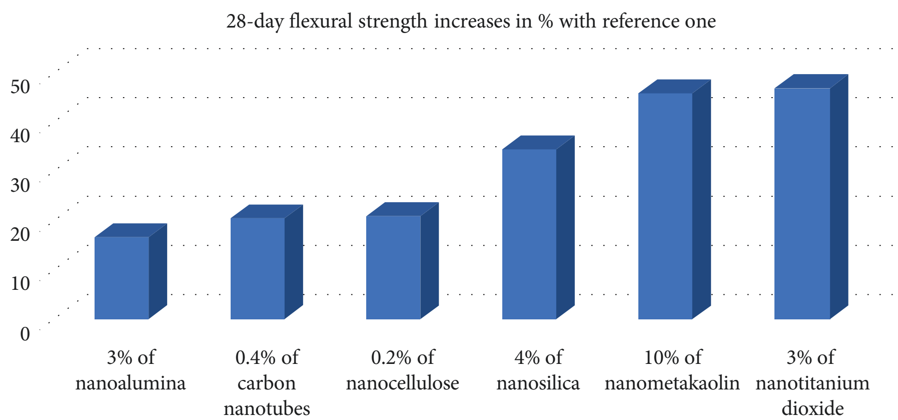

Figure 2: Twenty-eight-day flexural strength increase (%) [48, 64, 79, 86, 92, 96].

peak flexural capacity, the high probability of the fibers intercepting microcracks may play a favorable role in delaying the matrix fracture [92].

5. Conclusion

The development of early strength in concrete is enhanced by introducing nanomaterials that will positively impact the mechanical properties of cementitious materials. Improvement in flexural and compressive capacity can be observed in the initial assessment at a very nascent stage. During this review, a key finding was attributed to the pozzolanic filling effect, nucleation effect, and bridging development catalyzed the strengthening mechanism of nanomaterials. High surface mineral particles in cement mixtures need more water or plasticizers to make the concrete workable. The expanse of the literature suggests that the optimal percent of nanometakaolin is 10%, which boosts compressive capacity by 63% and flexural capacity by 46.8%. However, a trade-off ensures as the mechanical characteristics deteriorate with the gradual increase in NMK concentrations. According to this study, NS doses of up to 2% could improve compressive strength by 20.25% and flexural strength by 34.6% for 4% NS content. The characteristics of NS as an activator also aid in the hydration process. If the dose of NS is higher than 2%, the compressive and flexural capacities may be reduced. On the other side, increasing the amount of NT in material increases the compressive strength up to 23% and flexural strength to 47%, and using TiO_2 reduces air pollution. Nanoalumina at 1% increased compressive and flexural capacities by 46% and 16.7%, respectively, for a 3% replacement. The optimal CNT concentration for SCC is 0.5%, which increases compressive strength by up to 38.6% and flexural strength by up to 20.5% in ordinary standard concrete and by 38% in SCC. Nanocellulose is a plant-derived polymer that is safe for the environment and nontoxic during implementation. It significantly improves the mechanical qualities of concrete by substituting cement. The compressive strength increased by 25% with a 0.05% replacement of NC, and the flexural strength increased by 21% with a 0.2% substitution of NC with cement. These increments are explained in Figures 1 and 2.

When NMK concrete is compared to all six nanomaterials (NMK, NS, NT, NA, CNT, and nanocellulose), the compressive and flexural strength increases to 63% and 36%, respectively. However, several conclusions have been offered, but only a few are backed up by sufficient evidence, and the rest need to be confirmed. This is kept as a future work to be carried out by the authors. As a result, a holistic mechanistic framework should be built to determine the relationship between nanophenomena and mechanical characteristics and models capable of quantitatively analyzing the effects of nanomaterials on composite properties.

Abbreviations

NMK: Nanometakaolin
ACS: Air-cooled slag
OPC: Ordinary Portland cement
FRCC: Fiber-reinforced cementitious composite
HPC: High-performance concrete
SCC: Self-compacting concrete
ITZ: Interfacial transition zone
CAH: Calcium aluminate hydrate
CSH: Calcium silicate hydrate
NT: Nanotitanium dioxide
UHPC: Ultra-high-performance concrete
NA: Nano alumina
CNT: Carbon nanotube
RPC: Reactive powder concrete
MWCNT: Multiwalled carbon nanotubes
SCHPC: Self-compacting high-performance concrete.

Data Availability

The data supporting this study are from previously reported studies and datasets, which have been cited here.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] S. W. Tang, Y. Yao, C. Andrade, and Z. J. Li, "Recent durability studies on concrete structure," *Cement and Concrete Research*, vol. 78, Part A, pp. 143–154, 2015.

[2] V. Bonavetti, H. Donza, G. Menéndez, O. Cabrera, and E. F. Irassar, "Limestone filler cement in low w/c concrete: a rational use of energy," *Cement and Concrete Research*, vol. 33, no. 6, pp. 865–871, 2003.

[3] S. K. Agarwal, I. Masood, and S. K. Malhotra, "Compatibility of superplasticizers with different cements," *Construction and Building Materials*, vol. 14, no. 5, pp. 253–259, 2000.

[4] M. Abd Elrahman and B. Hillemeier, "Combined effect of fine fly ash and packing density on the properties of high-performance concrete: an experimental approach," *Construction and Building Materials*, vol. 58, pp. 225–233, 2014.

[5] R. Kishore, V. Bhikshma, and P. J. Prakash, "Study on strength characteristics of high strength rice husk ash concrete," *Procedia Engineering*, vol. 14, pp. 2666–2672, 2011.

[6] A. Kumar, T. Oey, G. P. Falla, R. Henkensiefken, N. Neithalath, and G. Sant, "A comparison of intergrinding and blending limestone on reaction and strength evolution in cementitious materials," *Construction and Building Materials*, vol. 43, pp. 428–435, 2013.

[7] V. M. Malhotra and P. K. Mehta, in *Pozzolanic and Cementitious Materials*, CRC Press, 2004.

[8] H. Li, H.-G. Xiao, J. Yuan, and J. Ou, "Microstructure of cement mortar with nanoparticles," *Composites Part B: Engineering*, vol. 35, no. 2, pp. 185–189, 2004.

[9] P. Balaguru and K. Chong, "Nanotechnology and concrete: research opportunities," in *Proceedings of the ACI Session on Nanotechnology of Concrete: Recent Developments and Future Perspectives*, pp. 15–28, National Science Foundation, Denver, USA, 2006.

[10] R. J.-M. Pellenq, N. Lequeux, and H. Van Damme, "Engineering the bonding scheme in C–S–H: the iono-covalent framework," *Cement and Concrete Research*, vol. 38, no. 2, pp. 159–174, 2008.

[11] R. Sahin and M. Oltulu, "New materials for concrete technology: nanopowders," in *33rd Conference on Our World in Concrete & Structures*, 2008.

[12] P. Hou, J. Qian, X. Cheng, and S. P. Shah, "Effects of the pozzolanic reactivity of nanoSiO_2 on cement-based materials," *Cement and Concrete Composites*, vol. 55, pp. 250–258, 2015.

[13] N. Crainic and A. T. Marques, "Nanocomposites: a state-of-the-art review," *Key Engineering Materials*, vol. 230-232, p. 656, 2002.

[14] K. Sobolev and S. P. Shah, "Nanotechnology of Concrete: Recent Developments and Future Perspectives *American Concrete Institute, ACI Special Publication*: Preface," in *American Concrete Institute, ACI Special Publication 254 SP*, 2008.

[15] F. Sanchez and K. Sobolev, "Nanotechnology in concrete – a review," *Construction and Building Materials*, vol. 24, no. 11, pp. 2060–2071, 2010.

[16] E. Jankowska and W. Zatorski, "Emission of nanosize particles in the process of nanoclay blending," in *2009 Third International Conference on Quantum, Nano and Micro Technologies*, IEEE, 2009.

[17] A. Hakamy, F. U. A. Shaikh, and I. M. Low, "Characteristics of nanoclay and calcined nanoclay-cement nanocomposites," *Composites Part B: Engineering*, vol. 78, pp. 174–184, 2015.

[18] M. Gesoglu, E. Güneyisi, D. S. Asaad, and G. F. Muhyaddin, "Properties of low binder ultra-high-performance cementitious composites: comparison of nanosilica and microsilica," *Construction and Building Materials*, vol. 102, Part 1, pp. 706–713, 2016.

[19] A. Khaloo, M. H. Mobini, and P. Hosseini, "Influence of different types of nano-SiO_2 particles on properties of high-performance concrete," *Construction and Building Materials*, vol. 113, pp. 188–201, 2016.

[20] M. S. M. Norhasri, M. S. Hamidah, and A. M. Fadzil, "Applications of using nano material in concrete: a review," *Construction and Building Materials*, vol. 133, pp. 91–97, 2017.

[21] H. Abdoli, H. R. Farnoush, H. Asgharzadeh, and S. K. Sadrnezhaad, "Effect of high energy ball milling on compressibility of nanostructured composite powder," *Powder Metallurgy*, vol. 54, no. 1, pp. 24–29, 2011.

[22] Y. D. Bharadwaz, B. G. Rao, V. D. Rao, and C. Anusha, "Improvement of biodiesel methanol blends performance in a variable compression ratio engine using response surface methodology," *Alexandria Engineering Journal*, vol. 55, no. 2, pp. 1201–1209, 2016.

[23] M. S. M. Norhasri, M. S. Hamidah, A. M. Fadzil, and O. Megawati, "Inclusion of nano metakaolin as additive in ultra-high performance concrete (UHPC)," *Construction and Building Materials*, vol. 127, pp. 167–175, 2016.

[24] S. P. Shah, M. S. Konsta-Gdoutos, Z. S. Metaxa, and P. Mondal, "Nanoscale modification of cementitious materials," in *Nanotechnology in Construction 3*, Z. Bittnar, P. J. M. Bartos, J. Němeček, V. Šmilauer and J. Zeman, Eds., pp. 125–130, Springer, Berlin, Heidelberg, 2009.

[25] T. P. Yadav, R. M. Yadav, and D. P. Singh, "Mechanical milling: a top down approach for the synthesis of nanomaterials

and nanocomposites," *Nanoscience and Nanotechnology*, vol. 2, no. 3, pp. 22–48, 2012.
[26] P.-C. Aïtcin, "Cements of yesterday and today: concrete of tomorrow," *Cement and Concrete Research*, vol. 30, no. 9, pp. 1349–1359, 2000.
[27] A. Mansi, N. H. Sor, N. Hilal, and S. M. A. Qaidi, "The impact of nano clay on normal and high-performance concrete characteristics: a review," *IOP Conference Series: Earth and Environmental Science*, vol. 961, Article ID 012085, 2022.
[28] J. S. Benjamin and R. D. Schelleng, "Dispersion strengthened aluminum-4 pct magnesium alloy made by mechanical alloying," *Metallurgical Transactions A*, vol. 12, pp. 1827–1832, 1981.
[29] K. T. Paul, S. K. Satpathy, I. Manna, K. K. Chakraborty, and G. B. Nando, "Preparation and characterization of nano structured materials from fly ash: a waste from thermal power stations, by high energy ball milling," *Nanoscale Research Letters*, vol. 2, Article ID 397, 2007.
[30] M. F. Ghazy, M. A. Abd Elaty, and R. S. Elkhoriby, "Performance of blended cement mortars incorporating nano-metakaolin particles at elevated temperatures," in *Proceeding of the International Conference on Advances in Structural and Geotechnical Engineering*, Tanta University, Hurghada, Egypt, 2015.
[31] A. D. Salman, "Studying the effect of nano-metakaolin admixture material on mechanical properties of oil well cement (OWC)," *Engineering and Technology Journal*, vol. 35, no. 9, 2017.
[32] K. Al-Jabri, H. Shoukry, and A. Abdel Aal, "Physico-mechanical properties of lime–silica fume pastes modified with nano-metakaolin," *Proceedings of the Institution of Civil Engineers-Structures and Buildings*, vol. 173, no. 9, pp. 627–634, 2020.
[33] M. Kaur, J. Singh, and M. Kaur, "Microstructure and strength development of fly ash-based geopolymer mortar: role of nano-metakaolin," *Construction and Building Materials*, vol. 190, pp. 672–679, 2018.
[34] F. Sajedi and H. A. Razak, "Comparison of different methods for activation of ordinary Portland cement-slag mortars," *Construction and Building Materials*, vol. 25, no. 1, pp. 30–38, 2011.
[35] Z. H. A. Alsallami, "Effect of sulfate in sand on some mechanical properties of nano metakaolin normal concrete," *Journal of Babylon University/Engineering Sciences*, vol. 24, no. 1, pp. 107–116, 2016.
[36] S. M. A. El-Gamal, M. S. Amin, and M. Ramadan, "Hydration characteristics and compressive strength of hardened cement pastes containing nano-metakaolin," *HBRC Journal*, vol. 13, no. 1, pp. 144–121, 2017.
[37] M. Heikal and N. S. Ibrahim, "Hydration, microstructure and phase composition of composite cements containing nano-clay," *Construction and Building Materials*, vol. 112, pp. 19–27, 2016.
[38] M. S. Morsy, Y. Al-Salloum, T. Almusallam, and H. Abbas, "Effect of nano-metakaolin addition on the hydration characteristics of fly ash blended cement mortar," *Journal of Thermal Analysis and Calorimetry*, vol. 116, pp. 845–852, 2014.
[39] M. J. Mahdavinejad, M. Nazari, and S. Khazforoosh, "Commercialization strategies for industrial applications of nanomaterials in building construction," *Advanced Materials Research*, vol. 829, pp. 879–883, 2013.
[40] L. Varghese, V. V. L. K. Rao, and L. Parameswaran, "Nanosilica-added concrete: strength and its correlation with time-dependent properties," *Proceedings of the Institution of Civil Engineers-Construction Materials*, vol. 172, no. 2, pp. 85–94, 2019.
[41] S. Kumar, A. Kumar, and J. Kujur, "Influence of nanosilica on mechanical and durability properties of concrete," *Proceedings of the Institution of Civil Engineers-Structures and Buildings*, pp. 781–788, 2019.
[42] M. Alhawat, A. Ashour, and A. El-Khoja, "Influence of using different surface areas of nano silica on concrete properties," *AIP Conference Proceedings*, vol. 2146, Article ID 020007, 2019.
[43] G. F. Huseien, N. H. A. Khalid, and J. Mirza, in *Nanotechnology for Smart Concrete*, CRC Press, 2022.
[44] N. J. Vickers, "Animal communication: when I'm calling you, will you answer too?" *Current Biology*, vol. 27, no. 14, pp. R713–R715, 2017.
[45] K.-Y. Liao, P.-K. Chang, Y.-N. Peng, and C.-C. Yang, "A study on characteristics of interfacial transition zone in concrete," *Cement and Concrete Research*, vol. 34, no. 6, pp. 977–989, 2004.
[46] M. Jalal, A. Pouladkhan, O. F. Harandi, and D. Jafari, "RETRACTED: comparative study on effects of class F fly ash, nano silica and silica fume on properties of high performance self-compacting concrete," *Construction and Building Materials*, vol. 94, pp. 90–104, 2015.
[47] L. G. Li, J. Y. Zheng, J. Zhu, and A. K. H. Kwan, "Combined usage of micro-silica and nano-silica in concrete: SP demand, cementing efficiencies and synergistic effect," *Construction and Building Materials*, vol. 168, pp. 622–632, 2018.
[48] F. Darabi-Golestan and A. Hezarkhani, "R- and Q-mode multivariate analysis to sense spatial mineralization rather than uni-elemental fractal modeling in polymetallic vein deposits," *Geosystem Engineering*, vol. 21, no. 4, pp. 226–235, 2018.
[49] A. E. AL-Salami, M. S. Morsy, S. Taha, and H. Shoukry, "Physico-mechanical characteristics of blended white cement pastes containing thermally activated ultrafine nano clays," *Construction and Building Materials*, vol. 47, pp. 138–145, 2013.
[50] A. A. Hashim, Z. Rodhan, and S. J. Abbas, "Fresh and hardened properties of self-compacting high-performance concrete containing nano-metakaolin as a partial replacement," *IOP Conference Series: Materials Science and Engineering*, vol. 928, Article ID 022036, 2020.
[51] M. K. Abed and Z. D. Habeeb, "Mechanical behavior of self-compacting concrete containing nano-metakaolin," *Journal of University of Babylon*, vol. 25, no. 5, pp. 1750–1758, 2017.
[52] H. Shoukry, "Development of nano modified eco-friendly green binders for sustainable construction applications," in *Nano Hybrids and Composites*, vol. 24, Trans Tech Publications Ltd., 2019.
[53] S. A. Abo-El-Enein, M. S. Amin, F. I. El-Hosiny, S. Hanafi, T. M. ElSokkary, and M. M. Hazem, "Pozzolanic and hydraulic activity of nano-metakaolin," *HBRC Journal*, vol. 10, no. 1, pp. 64–72, 2014.
[54] A. Nadeem, S. A. Memon, and T. Y. Lo, "The performance of fly ash and metakaolin concrete at elevated temperatures," *Construction and Building Materials*, vol. 62, pp. 67–76, 2014.
[55] A. M. Ibrahem, S. A. Al-Mishhadani, and Z. H. Naji, "The effect of nano metakaolin material on some properties of concrete," *Diyala Journal of Engineering Sciences*, vol. 6, no. 1, pp. 50–61, 2013.
[56] A. M. Fadzil, M. S. Mohd Norhasri, M. S. Hamidah, M. R. Zaidi, and J. Mohd Faizal, "Alteration of nano

metakaolin for ultra high performance concrete," in *In CIEC 2013*, pp. 887–894, Springer, Singapore, 2014.

[57] M. S. Morsy, Y. A. Al-Salloum, H. Abbas, and S. H. Alsayed, "Behavior of blended cement mortars containing nano-metakaolin at elevated temperatures," *Construction and Building Materials*, vol. 35, pp. 900–905, 2012.

[58] P.-M. Zhan, Z.-H. He, Z.-M. Ma et al., "Utilization of nano-metakaolin in concrete: a review," *Journal of Building Engineering*, vol. 30, Article ID 101259, 2020.

[59] G. V. Rathnamala, R. M. Ashwini, P. Sai, K. Y. Chowdary, and C. Harshitha, "Analysis of drinking water quality and mode of storage in Dodballapur Taluk," *Solid State Technology*, vol. 63, no. 5, pp. 945–957, 2020.

[60] H. Shoukry, M. F. Kotkata, S. A. Abo-el-Enein, and M. S. Morsy, "Flexural strength and physical properties of fiber reinforced nano metakaolin cementitious surface compound," *Construction and Building Materials*, vol. 43, pp. 453–460, 2013.

[61] S. Tanveer Hussain and K. V. S. Gopala Krishna Sastry, "Study of strength properties of concrete by using micro silica and nano silica," *International Journal of Research in Engineering and Technology*, vol. 3, no. 10, pp. 103–108, 2014.

[62] M. M. Salman, K. M. Eweed, and A. M. Hameed, "Influence of partial replacement TiO_2 nanoparticles on the compressive and flexural strength of ordinary cement mortar," *Al-Nahrain Journal for Engineering Sciences*, vol. 19, no. 2, pp. 265–270, 2016.

[63] H. Noorvand, A. A. Abang Ali, R. Demirboga, N. Farzadnia, and H. Noorvand, "Incorporation of nano TiO_2 in black rice husk ash mortars," *Construction and Building Materials*, vol. 47, pp. 1350–1361, 2013.

[64] Z. Li, B. Han, X. Yu et al., "Effect of nano-titanium dioxide on mechanical and electrical properties and microstructure of reactive powder concrete," *Materials Research Express*, vol. 4, no. 9, Article ID 095008, 2017.

[65] A. H. Shekari and M. S. Razzaghi, "Influence of nano particles on durability and mechanical properties of high performance concrete," *Procedia Engineering*, vol. 14, pp. 3036–3041, 2011.

[66] A. Nazari and S. Riahi, "RETRACTED: TiO_2 nanoparticles effects on physical, thermal and mechanical properties of self-compacting concrete with ground granulated blast furnace slag as binder," *Energy and Buildings*, vol. 43, no. 4, pp. 995–1002, 2011.

[67] B. Han, Z. Li, L. Zhang et al., "Reactive powder concrete reinforced with nano SiO_2-coated TiO_2," *Construction and Building Materials*, vol. 148, pp. 104–112, 2017.

[68] N. Salemi, K. Behfarnia, and S. A. Zaree, "Effect of nanoparticles on frost durability of concrete," *Asian Journal of Civil Engineering (BHRC)*, vol. 15, no. 3, pp. 411–420, 2014.

[69] P. Hemalatha and K. Ramujee, "Influence of nano material (TiO_2) on self compacting geo polymer concrete containing flyash, GGBS and wollastonite," *Materials Today: Proceedings*, vol. 43, Part 2, pp. 2438–2442, 2021.

[70] N. J. Saleh, R. I. Ibrahim, and A. D. Salman, "Characterization of nano-silica prepared from local silica sand and its application in cement mortar using optimization technique," *Advanced Powder Technology*, vol. 26, no. 4, pp. 1123–1133, 2015.

[71] S. Chithra, S. R. R. Senthil Kumar, and K. Chinnaraju, "The effect of colloidal nano-silica on workability, mechanical and durability properties of high-performance concrete with copper slag as partial fine aggregate," *Construction and Building Materials*, vol. 113, pp. 794–804, 2016.

[72] K. Sobolev and M. F. Gutiérrez, "How nanotechnology can change the concrete world," *American Ceramic Society Bulletin*, vol. 84, no. 11, pp. 16–20, 2005.

[73] K. Behfarnia, A. Azarkeivan, and A. Keivan, "The effects of TiO_2 and ZnO nanoparticles on physical and mechanical properties of normal concrete," *Asian Journal of Civil Engineering (BHRC)*, vol. 14, no. 4, pp. 517–531, 2013.

[74] T. Meng, Y. Yu, X. Qian, S. Zhan, and K. Qian, "Effect of nano-TiO_2 on the mechanical properties of cement mortar," *Construction and Building Materials*, vol. 29, pp. 241–245, 2012.

[75] R. Gowda, H. Narendra, D. Rangappa, and R. Prabhakar, "Effect of nano-alumina on workability, compressive strength and residual strength at elevated temperature of cement mortar," *Materials Today: Proceedings*, vol. 4, Part 3, no. 11, pp. 12152–12156, 2017.

[76] N. Farzadnia, A. A. Abang Ali, and R. Demirboga, "Characterization of high strength mortars with nano alumina at elevated temperatures," *Cement and Concrete Research*, vol. 54, pp. 43–54, 2013.

[77] H. I. Ahmed, "Behavior of magnetic concrete incorporated with Egyptian nano alumina," *Construction and Building Materials*, vol. 150, pp. 404–408, 2017.

[78] P. Jaishankar and C. Karthikeyan, "Characteristics of cement concrete with nano alumina particles," *IOP Conference Series: Earth and Environmental Science*, vol. 80, Article ID 012005, 2017.

[79] E. Mohseni, M. M. Khotbehsara, F. Naseri, M. Monazami, and P. Sarker, "Polypropylene fibre reinforced cement mortars containing rice husk ash and nano-alumina," *Construction and Building Materials*, vol. 111, pp. 429–439, 2016.

[80] K. Behfarnia and N. Salemi, "The effects of nano-silica and nano-alumina on frost resistance of normal concrete," *Construction and Building Materials*, vol. 48, pp. 580–584, 2013.

[81] T. Ansari rad, J. Tanzadeh, and A. Pourdada, "Laboratory evaluation of self-compacting fiber-reinforced concrete modified with hybrid of nanomaterials," *Construction and Building Materials*, vol. 232, Article ID 117211, 2020.

[82] J. Szymanowski and Ł. Sadowski, "The development of nanoalumina-based cement mortars for overlay applications in concrete floors," *Materials*, vol. 12, no. 21, Article ID 3465, 2019.

[83] T. C.h Madhavi, P. Pavithra, S. B. Singh, and S. B. Vamsi Raj, "Effect of multiwalled carbon nanotubes on mechanical properties of concrete," *International Journal of Science and Research*, vol. 2, no. 6, pp. 166–168, 2012.

[84] S. Li, Y. Zhang, S. Lin, J. Yan, and S. Du, "Effects of nano-SiO_2 coated multi-walled carbon nanotubes on mechanical properties of cement-based composites," *Construction and Building Materials*, vol. 281, Article ID 122577, 2021.

[85] M. R. Irshidat, N. Al-Nuaimi, S. Salim, and M. Rabie, "Carbon nanotubes dosage optimization for strength enhancement of cementitious composites," *Procedia Manufacturing*, vol. 44, pp. 366–370, 2020.

[86] G. R. Vesmawala, A. R. Vaghela, K. D. Yadav, and Y. Patil, "Effectiveness of polycarboxylate as a dispersant of carbon nanotubes in concrete," *Materials Today: Proceedings*, vol. 28, Part 2, pp. 1170–1174, 2020.

[87] Q. I. Barodawala, S. G. Shah, and S. G. Shah, "Modifying the strength and durability of self compacting concrete using carbon nanotubes," in *Proceedings of the International Conference on Advances in Construction Materials and Structures (ACMS-2018)*, pp. 7-8, IIT Roorkee, Roorkee, Uttarakhand, India, 2018.

[88] L. Lu, D. Ouyang, and W. Xu, “Mechanical properties and durability of ultra-high strength concrete incorporating multi-walled carbon nanotubes,” *Materials*, vol. 9, no. 6, Article ID 419, 2016.

[89] L. I. Nasibulina, I. V. Anoshkin, A. G. Nasibulin, A. Cwirzen, V. Penttala, and E. I. Kauppinen, “Effect of carbon nanotube aqueous dispersion quality on mechanical properties of cement composite,” *Journal of Nanomaterials*, vol. 2012, Article ID 169262, 6 pages, 2012.

[90] L. I. Nasibulina, I. V. Anoshkin, S. D. Shandakov et al., “Direct synthesis of carbon nanofibers on cement particles,” *Transportation Research Record*, vol. 2142, no. 1, pp. 96–101, 2010.

[91] A. G. Nasibulin, S. D. Shandakov, L. I. Nasibulina et al., “A novel cement-based hybrid material,” *New Journal of Physics*, vol. 11, Article ID 023013, 2009.

[92] O. A. Hisseine, W. Wilson, L. Sorelli, B. Tolnai, and A. Tagnit-Hamou, “Nanocellulose for improved concrete performance: a macro-to-micro investigation for disclosing the effects of cellulose filaments on strength of cement systems,” *Construction and Building Materials*, vol. 206, pp. 84–96, 2019.

[93] S. W. M. Supit and T. Nishiwaki, “Compressive and flexural strength behavior of ultra-high-performance mortar reinforced with cellulose nano-fibers,” *International Journal on Advanced Science, Engineering and Information Technology*, vol. 9, no. 1, pp. 365–372, 2019.

[94] S. A. Ghahari, L. N. Assi, A. Alsalman, and K. E. Alyamaç, “Fracture properties evaluation of cellulose nanocrystals cement paste,” *Materials*, vol. 13, no. 11, Article ID 2507, 2020.

[95] A. E. Al-Salami, H. Shoukry, and M. S. Morsy, “Thermo-mechanical characteristics of blended white cement pastes containing ultrafine nano clays,” *International Journal of Green Nanotechnology*, vol. 4, no. 4, pp. 516–527, 2012.

[96] R. Yu, P. Spiesz, and H. J. H. Brouwers, “Effect of nano-silica on the hydration and microstructure development of ultra-high-performance concrete (UHPC) with a low binder amount,” *Construction and Building Materials*, vol. 65, pp. 140–150, 2014.

[97] W. Li, Z. Huang, F. Cao, Z. Sun, and S. P. Shah, “Effects of nano-silica and nano-limestone on flowability and mechanical properties of ultra-high-performance concrete matrix,” *Construction and Building Materials*, vol. 95, pp. 366–374, 2015.

[98] B. Ma, H. Li, J. Mei, X. Li, and F. Chen, “Effects of nano-TiO_2 on the toughness and durability of cement-based material,” *Advances in Materials Science and Engineering*, vol. 2015, Article ID 583106, 10 pages, 2015.

[99] G. Rathnamala, R. Ashwini, and N. Babitha, “Domestic environmental destructions due to lack of solid waste management in rural areas,” *Advances in Mathematics: Scientific Journal*, vol. 10, no. 3, pp. 1807–1819, 2021.

[100] B. Han, Y. Wang, S. Dong et al., “Smart concretes and structures: a review,” *Journal of Intelligent Material Systems and Structures*, vol. 26, no. 11, pp. 1303–1345, 2015.

[101] S. Jiang, D. Zhou, L. Zhang et al., “Comparison of compressive strength and electrical resistivity of cementitious composites with different nano- and micro-fillers,” *Archives of Civil and Mechanical Engineering*, vol. 18, no. 1, pp. 60–68, 2018.

[102] Z. Li, S. Ding, X. Yu, B. Han, and J. Ou, “Multifunctional cementitious composites modified with nano titanium dioxide: a review,” *Composites Part A: Applied Science and Manufacturing*, vol. 111, pp. 115–137, 2018.

[103] R. M. Ashwini, G. V. Rathnamala, G. D. Kumar, M. Manikiran, and N. Sharath, “Dynamic analysis of Rc frame structure with & without infill when subjected to seismic load,” *Solid State Technology*, vol. 63, no. 5, pp. 1961–1971, 2020.

[104] Y. Cao, P. Zavaterri, J. Youngblood, R. Moon, and J. Weiss, “The influence of cellulose nanocrystal additions on the performance of cement paste,” *Cement and Concrete Composites*, vol. 56, pp. 73–83, 2015.

[105] G. V. Rathnamala and G. P. Shivashankara, “An evidence-based approach towards identifying household emerging pollutants in rural areas in Southern Karnataka,” *Journal of Water, Sanitation, and Hygiene for Development*, vol. 12, no. 6, pp. 498–516, 2022.